Fluvial to shelfal strata of the Late Cretaceous to Paleogene Dorotea and Tres Pasos Formations, Magallanes Basin, El Calafate, Argentina

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ABSTRACT

Late Cretaceous to Paleogene strata of the Tres Pasos and Dorotea formations, exposed along the Andean margin in the Santa Cruz Province of Southern Argentina, were deposited in the Magallanes Basin, a retro-arc foreland basin. These strata are well exposed east of the Cordillera de los Andes thrust belt and were studied approximately 50 km east of the leading thrust. Discontinuous exposure of the upper 190 m (~10%) of the Tres Pasos Formation contains at least 7 parasequences containing upward-coarsening siltstones and sandstones, with hummocky and swaley cross-stratification. These are interpreted as distal to middle shelfal deposits of the lower shoreface. The top of the Tres Pasos Formation is an erosional unconformity, and overlain by over 200 meters of Dorotea Formation. Outcrops of the Dorotea Formation can be traced laterally for over 15 km of dip-oriented section. The Dorotea Formation is divided into two informal stratigraphic units, separated by a sequence boundary. Both are dominated by fluvial strata and overbank deposits. At least 14 parasequences are identified in the lower unit and average 5.5 m in thickness. Parasequences are comprised of upward-fining channel-fill sandstones and associated overbank fines, which are interpreted to be low sinuosity meandering stream and floodplain deposits. The upper unit contains 19 parasequences that average 7.6 m in thickness. These parasequences also contain channel fill sandstone, which are coarser and are interpreted as the deposits of higher energy fluvial systems. In addition to an overall increase in average grain size, many of the channelized sandstones are conglomeratic at the base. Unlike the lower unit, no lateral accretion is seen in the

upper unit, and the majority of these channel-fill sandstones are interpreted as deposits of high-energy, braided fluvial systems. No significant lateral facies changes were observed across the 10 km extent of outcrop exposure.

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INTRODUCTION

The purpose of this study was to determine depositional environments of the Late Cretaceous to Paleocene Tres Pasos and Dorotea formations in the Santa Cruz Province of southern Argentina and place these strata in a sequence stratigraphic framework. Thin-section petrography was used for provenance study, and a paleocurrent analysis was completed to better understand the basin-fill history. In addition, the transition between the Tres Pasos and Dorotea formations was studied to see whether the formation boundary recorded a tectonic event in the basin or in the associated thrust belt.

The Tres Pasos and Dorotea formations were deposited in the Magallanes retro-arc foreland basin. The basin is floored by deep-water deposits of the Punta Barossa and Cerro Toro formations, overlain by the distal shelf deposits of the Tres Pasos Formation and purported shallow water deposits of the Dorotea Formation. The deep-water strata within the foreland basin are well studied (Bernhardt et al., 2011; Bernhardt et al., 2012; Fildani and Hessler, 2005; Jobe et al., 2010; Romans et al., 2010; Romans et al., 2011), however, purported shallow marine strata of the Dorotea Formation (Covault et al., 2009; Fildani et al., 2008; Fosdick et al., 2011; Hubbard et al., 2010; Romans et al., 2011) had not been studied in detail. Distal shelfal marine strata (Tres Pasos Formation) have been the focus of some studies (Shultz et al., 2005; Covault et al., 2009; Hubbard et al., 2010; Romans et al., 2011), but the transition between marine and continental deposition is not documented for the Lago Argentino area. Preliminary studies of the Chilean succession of the Tres Pasos and Dorotea formations propose a continuous succession from deep water to distal shelf to shallow water successions across this formation boundary (Fig. 1)(Macellari et al., 1989; Fildani et al., 2008; Covault et al., 2009; Hubbard et al., 2010; Fosdick et al., 2011; Romans et al., 2011). Paleogeographic reconstruction of the Magallanes foreland basin for the Cretaceous depicts a southward propagating depositional slope and axial-parallel fill of the basin (Romans et al., 2011; Hubbard et al., 2010). The Dorotea Formation, near El Calafate, Argentina, is well exposed along a 10 km transect (Fig. 2). The study area is approximately 25 km north of a previous-studied time-equivalent section in the Ultima Esperanza District of Chile (Katz, 1963; Covault et al., 2009; Fildani et al., 2008; Fosdick et al., 2011; Hubbard et al., 2010; Romans et al., 2011), and is located 50 km east of the leading thrust of the Patagonian fold-and-thrust belt.

TECTONIC AND STRATIGRAPHIC CONTEXT

The Magallanes Foreland Basin overlies a back-arc basin, which has a complicated and complex history. The southern Patagonian Andes was site of an extensional tectonics in the Middle to Late Jurassic associated with the breakup of Gondwana (Bruhn et al., 1978; Gust et al., 1985; Wilson, 1991; Pankhurst et al., 2000; Calderón et al., 2007). The extension corresponds to the initiation of the developing backarc Rocas Verdes Basin near the Pacific margin of southern South America (Dalziel and Cortés, 1972; Suárez, 1979; Dalziel, 1981; Wilson, 1991). This back-arc basin widened southward from its deduced northern limit near 50°S (Dalziel and Cortés, 1972; Calderón et al., 2007).

The Rocas Verdes Backarc Basin is floored by quasi-oceanic crust typified by the Sarmiento and Tortuga ophiolites (Allen, 1982; Stern, 1980; Alabaster and Storey, 1990). The transition from the Late Jurassic-Early Cretaceous extensional Rocas Verdes backarc basin (Tobífera and Zapata formations) to the Cretaceous contractile Magallanes retroarc foreland basin coincides with increased subduction along the Pacific margin and faster spreading rates of the South Atlantic Ocean (Rabinowitz and La Brecque, 1979; Dalziel, 1986; Ramos, 1988). The spreading rates along the Pacific ridges accelerated in the Neocomian (Bartolini and Larson, 2001) and, combined with increased spreading of the Atlantic ridges, possibly resulted in the evolution of the Rocas Verdes Basin into a compressional regime, and subsequently closing the backarc basin in the Early Cretaceous (Fildani and Hessler, 2005). This caused a transition from an extensional arc to a compressional arc, which created a fold and thrust belt. This led to crustal shortening and ultimately the closure of the Rocas Verdes Basin, the development of the Andean fold-and-thrust belt, and linked foreland subsidence (Suárez and Pettigrew, 1976; Wilson, 1991; Fildani and Hessler, 2005).

The initial inversion of the Rocas Verdes Basin occurred during deposition of the upper Zapata Formation, as hypothesized by Fildani et al. (2008). A well-established contractional phase at 92 Ma coincided with deposition of turbidites of the overlying

Upper Cretaceous Punta Barrosa Formation (Wilson, 1991; Fildani et al., 2003; Fildani and Hessler, 2005; Bernhardt et al., 2011). The deep-water, conglomeratic Cerro Toro Formation and overlying slope and purported deltaic systems of the Tres Pasos and Dorotea formations record continual subsidence and sedimentation. Sediment was sourced from denudation of an active arc and fold-thrust belt during the Late Cretaceous (Katz, 1963; Scott, 1966; Natland, 1974; Biddle et al., 1986; Wilson, 1991; Fildani and Hessler, 2005; Romans, 2008b). The Upper Cretaceous Cerro Toro Formation is represented by deep-water sedimentation in the Magallanes Foreland Basin and was deposited at depths up to 2000 m (Natland et al., 1974). Conglomerate-filled channels developed along the length of the axial foredeep (Winn and Dott, 1979; Hubbard et al., 2008), and punctuate the shale-dominated succession. The thickness of the formation spans from a proximal ~1000 m (Crane, 2004) to ~2500 m in the more distal portions of the axial channel belt (Hubbard, 2006).

The overlying Late Cretaceous Tres Pasos Formation is interpreted to represent upward shallowing of the Magallanes Basin (Smith, 1977; Wilson, 1991; Shultz et al., 2005). In the Ultima Esperanza District of Chile (~25 km SW from study area), the Tres Pasos Formation is interpreted to be a well-developed slope succession dominated in its lower part by mudstone-rich mass wasting deposits punctuated by lenticular sandstone successions (Shultz et al., 2005). The Tres Pasos Formation shallows upward into the overlying purported deltaic and shallow-marine deposits of the Dorotea Formation, which has not been studied in detail near Lago Argentino. The linked shelf-and-slope system prograded southward filling the foredeep during the Late Cretaceous (Smith

1977; Macellari et al. 1989; Shultz et al. 2005; Romans et al. 2008a).

FACIES ANALYSIS

Three extensive outcrops of the upper ~10% of the Tres Pasos Formation and the majority of the Dorotea Formation were measured on the decimeter scale along a 10 km W-E transect (Fig. 2 and 3). The sections recorded range from 340-420 m in thickness (Fig 3). Detailed descriptions include lithology, grain size, bedding surfaces, and physical and biogenic sedimentary structures. Sections were measured on a bed-by-bed basis, using the methods of Campbell (1967). Facies were defined based on vertical grain-size trends, the vertical succession of sedimentary structures, and fossil content.

There is no well-defined datum to correlate across the three measured sections, so a floating datum was used. A bed was traced with the aid of binoculars from sections 2 and 3, and was used with confidence as a datum between those sections. Between sections 1 and 2, however, outcrop was not continuously exposed, making the correlation difficult. The datum used to correlate sections 1 and 2 is an approximated datum, and because of this, all estimates of relief in this study are based solely on correlation of the measured sections 2 and 3. The entire Dorotea Formation is not exposed in any of the sections. After stratigraphic sections were measured, and the floating datum was established, it was apparent that the upper portion of the Dorotea Formation was missing from sections 2 and 3. Although measured section 1 is the most complete section, it is also incomplete. The upper part of the formation is present, but the quality of the outcrop diminishes upsection, where the outcrop is either covered or inaccessible. For this reason, an estimated 110 m of section was not measured at this locality. Interpretations of the Dorotea Formation in this study are based on accessible exposures of the formation.

Paleocurrent data provide the dominant direction of flow, which shows the orientation of the outcrop exposure relative to channel and bar trends. Data were recorded using three-dimensional exposures of individual limbs of cross-strata, following the technique of DeCelles et al. (1983). Axes of trough crossbeds were generally aligned parallel to local primary flow direction, and paleocurrent data collected from the axes of individual channels show a relatively small degree of scatter.

Four facies are identified within the exposed Tres Pasos and the Dorotea formations along the 10 km transect of this study. The upper contact of the Dorotea Formation was not seen. This could be due to weathering/loss of the outcrop. These four facies are described and interpreted below.

Facies of the Tres Pasos Formation

Facies 1: Upward-coarsening succession of interbedded hummocky to swaly cross-stratification and thinly bedded siltstones

Description. Facies 1 is observed in the lower 65 m and 190 m of the Aerosilla and Alta Vista measured sections, respectively, and represents the upper ~3% and 10% of this formation. It consists predominantly of upward-coarsening successions of interbedded hummocky-to-swaly, cross-stratified, very fine (4-3 ɸ) -to-fine (2-3 ɸ) grained sandstones. These beds are light tan in color and range from 0.3-1 m in thickness, and are interbedded with thinly bedded siltstone and sandstone (Fig. 4A). Hummocky cross-stratified beds are sharp based, and beds pinch and swell laterally, and become amalgamated up section. Thin organic laminae define bedding surfaces between juxtaposed beds. Hummocky beds are interbedded with several centimeters-thick, fine-grained siltstone and sandstone beds. These thin interbeds are predominantly locally burrowed by *Cylindrichnus*, *Schaubcylindrichnus,* and unidentified bioturbation at the top of beds.

Depositional Processes / Depositional Environment. Hummocky cross-stratification reflects deposition from large-scale oscillatory currents associated with storm events in the lower shoreface (Harms et al. 1975; Dott and Bourgeois 1982; Southard et al. 1990). Hummocky cross-stratification usually develops where unidirectional currents are weak, and water depths are shallow enough for wave orbits to remain strong and large, but also deep enough for waves to remain symmetrical (Dott and Bourgeois 1982; Dumas and Arnott 2006). The thin, bioturbated interbeds are likely prolonged periods of fine-grained ‘‘background’’ sedimentation (i.e., non-storm) in the lower shoreface or offshore. The preservation of hummocky cross-stratified sandstones is probably the result of punctuated storm events that generated the hummocky beds (Wheatcroft 2000; Shanmugam 2008).

Swaly cross-stratification reflects deposition resulting from combined oscillatory and unidirectional currents (Walker and Plint 1992; Dumas and Arnott 2006). Amalgamated swaly cross-stratified beds develop in shallower environments relative to hummocky beds, where unidirectional currents are dominant (Walker and Plint 1992; Dumas and Arnott 2006). Organic detritus may have been transported offshore by strong unidirectional currents, such as fluvial, tidal, or storm currents.

Facies of the Dorotea Formation

Facies 2: Upward-fining sandstone "A"

Description. This facies comprises upward-fining, wedge/festoon shaped cross-stratified sandstone with burrows and rip-up clasts. The sandstones average 5.5 m thick, with a maximum thickness of 11 meters and thin laterally to less than 2 m. These sandstones continue laterally for 100's of meters and are encased in siltstone and mudstone of facies 3 (Fig. 4B). Sandstones have a scoured base and an upward-fining grain size profile ranging from coarse (0-1 ϕ) to fine (2-3 ϕ). Wedge-and festoon-shaped cross bedding is abundant in each sandstone (Fig. 4C). Cross bed thickness decreases vertically, ranging from ~0.4 m at the base of the sandstones and decreasing to ~0.1 m at the top. Lateral accretion surfaces are limited and were ~2.5 m in height. The paleocurrent readings obtained from these cross beds average 138° (N=67) (Fig. 3). Drapes of organic silt occur along bedding planes of some cross bed. Isolated flaser bedding occurs at the top of some sandstones (upper most 0.1 m to 1 m), overlying the wedge and festoon cross-stratification. Rip-up clasts, wood clasts, and pebbles up to 2cm occur locally along the basal scours of the sandstones. *Cylindrichnus, Diplocraterion* (Fig. 4D), *Ophiomorpha*, and *Shaubcylindrichnus* are seen in varying amounts ranging from 1-20 burrows/m^2. Abraded shells, including *Inoceramus* and *Siliqua,* are more abundant in some sandstones, especially those lower in the section (Fig. 4E). *Diplocraterion* only occurs at the top of the sandstones. Burrows are not seen in the same beds with shells.

Depositional Processes/Depositional Environment. The upward fining sandstones are interpreted as channel-fill deposits. The upward-fining profile with lateral accretion surfaces is typical of deposition from point bar migration (Allen, 1963; Miall, 1996; Bridge, 2006). The presence of only a few lateral accretion surfaces indicates that while these channels had a lateral migration component (Allen, 1963), the channel-fills deposits are low sinuosity meandering channels. The wedge to festoon shaped cross-stratification are deposits of three-dimensional, migrating bar forms (Harms et al., 1975; Miall, 1996). Downstream migrating bars can occur in both meandering and braided river systems (Bridge, 2006).

The isolated flaser bedding is formed when individual ripples are later draped by mud, deposited during lower-energy flow velocities. These may or may not indicate tidal influence. The presence of *Cylindrichnus, Diplocraterion, Ophiomorpha, and Shaubcylindrichnus*, as well as abraded shells (e.g. *Inoceramus* and *Siliqua*), supports the interpretation that these channel fill sandstones were deposited in close proximity to the coast and may represent estuarine deposits. While the source of the abraded shells may have been the underlying Tres Pasos Formation, the trace fossils are formed in situ.

Facies 3: Structureless, bioturbated fine grain deposits

Description. Laterally continuous sandy siltstones, and mudstones overlie and underlie channel-fill sandstones of facies 2. The sandy siltstones are poorly laminated to non-laminated and poorly bedded. Laminae are mm-cm scale in thickness. The thickness of this facies ranges from a few cm to 5 m. In places, bioturbation exists throughout the facies, resulting in a mottled texture. Sandy siltstones and mudstones range from medium to dark gray in color and contain disseminated organic matter and mm to cm scale fragments of wood. Blocky texture is seen in a small portion of the mudstones. Rooting is limited, but is observed in the sandy siltstones and has clay infill that tapers downward.

Depositional Processes / Depositional Environment. Sandy siltstones and mudstones represent floodplain and overbank deposits associated with the meandering channels of facies 2. The development of thick (up to 5 m) bioturbated overbank fines indicate deposition in a low gradient system, which could be have been floodplain (Miall, 1996). The predominant gray coloration, commonly attributed to the presence of organic material and probably iron sulfide, commonly occurs in a humid climate (cf. McBride, 1974). The absence of lamination in the mudstones and siltstones is attributed to bioturbation, which is abundant in overbank deposits (Miall, 1996; Bridge, 2006). Blocky pedogenic structure is interpreted to be from poorly developed paleosols. The lack of rooting could be due to abundant bioturbation of organisms.

Facies 4: Upward-fining sandstones and conglomerates "B"

***Description**.* Facies 4 consists of laterally persistent, upward-fining sandstones that average 7.6 m in thickness. These sandstones contain multiple internal scour surfaces with up 2-3 meters of relief. Scour surfaces are defined by a sudden increase in grain size, concentration of rip-up clasts, and limited wood fragments (Fig. 4G). Sandstones display an upward-fining grain size profile with very coarse (-1-0 ϕ) to cobble-size (-6 --8 ϕ) clasts up to 7 cm in diameter at the base, to fine-grained (2-3 ϕ) at the top. Sandstones are commonly nested, with the overlying sandstone truncating the underlying sandstone. The upward-fining profile is not always fully preserved when sandstones are truncated. The basal scour of nested sandstones have a larger difference of grain size and larger relief, compared to that of internal scour surfaces, which have less of a grain size difference and a lower relief. The upward-fining profile is usually seen in the upper-most sandstone of the nested sandstones. The mode grain size (-2.5 ϕ) of the sandstones in facies 4 is much larger than the mode grain size (1.5 ϕ) of the sandstones present in facies 2. Trough-and wedge-shaped cross-beds, ranging from ~0.1 to ~0.5 m in thickness, occur throughout the nested sandstones complex. Between scour surfaces, the cross bed thickness decreases vertically. The paleocurrent reading obtained from this facies average 150° (N=65). Unlike the sandstones in facies 2, lateral accretion surfaces are absent in this facies.

Depositional Processes/Depositional Environment. Facies 4 represents a complex of nested and amalgamated, fluvial channel-fill deposits. The channel-fill sandstones are interpreted to be deposited in a high-gradient fluvial system. The increase in grain size from facies 2 to facies 4 indicates an increase in energy of the fluvial system (Hjulström, 1935), which is interpreted to reflect an increase in the gradient (Schumm, 1981). The 0.5 m cross-stratification reflects deposition from the downstream migration of large-scale barforms (Miall, 1996; Bridge, 2006). The absence of lateral accretion surfaces indicates that the system did not have a prominent lateral migration component and was not highly meandering (Allen, 1963). Although downstream migrating bedforms can occur in both meandering and braided river systems (Bridge, 2006), the dominance of these bedforms and lack of lateral migrating point bar deposits, as well as the nested nature of the channel-fill sandstones, suggests these sandstones represent deposition from braided rivers (Miall, 1996; Bridge and Lunt, 2006).

STRATIGRAPHY

Marine strata of the Tres Pasos Formation contain seven upward-coarsening successions (facies 1 – distal LSF). The thickness of these successions increases up-section from ~15 m to ~30 m. These upward-coarsening successions are interpreted as parasequences. Successive parasequences become more sand rich and more proximal. Based on the stacking pattern, these marine successions form a progradational parasequence set. Hummocky cross-stratified sandstones of the stratigraphically highest occurrence of facies 1 are truncated and overlain by channelized sands (facies 2) of the Dorotea Formation. This erosional surface (and the formation contact), has up to 20 m of relief, and where observed, is always overlain by the sandstones of facies 2.

Outcrops of the Dorotea Formation are limited to facies 2, 3 and 4. Based on facies analysis and the distribution of these facies, the Dorotea Formation is divided into two informal stratigraphic units. The lower unit comprises approximately one-third (100-150 m) of the Dorotea Formation and consists of interbedded lower energy channelized sandstones (facies 2) and overbank deposits (facies 3). These strata represent high accommodation fill with a low net-to-gross sandstone-to-shale ratio. At least fourteen single-story to vertically stacked or nested sandstones (facies 2) are observed in a vertical section. The upper contact of each channel-fill sandstone is interpreted as a flooding surface/parasequence boundary, and so each vertically stacked channel-fill sandstone is interpreted as part of a separate parasequence. Using this approach, at least fourteen parasequences are interpreted in the lower part of the Dorotea Formation.

The upper unit of the Dorotea Formation comprises approximately two-thirds (~230 m) of the formation and consists of interbedded, relatively higher energy channelized sandstones (facies 4) and overbank deposits (facies 3). Laterally continuous siltstones (facies 3) overlie and underlie channel-fill sandstones, essentially encasing them. The upper unit contains nineteen predominantly nested channel-fill sandstones, many of which can be traced laterally for hundreds to thousands of meters (Fig. 4F). The deeper and more extensive internal scours of the channelized sandstones represent the base of individual channel-fill sandstones that are vertically stacked. Up to three channel-fill sandstones occur nested vertically. The net-to-gross sandstone-to-shale ratio is lower in the lower unit compared to the upper unit. In part, this may reflect the preferential measuring of outcrops where exposures are sandstone rich and not covered by vegetation, which favors the finer-grained facies.

The contact between the upper and lower unit is defined at the base of the first appearance of facies 4 (upward fining sandstones and conglomerates B). It occurs approximately 100-150 m above the Tres Pasos-Dorotea Formation contact and exhibits approximately 25 m of erosional relief. This contact is interpreted as a sequence boundary because a succession of higher energy fluvial deposits (upper unit) erosionally overlie a succession of lower energy fluvial deposits (lower unit). Channel-fills within the upper unit are thicker and coarser grained, which reflect an increase in fluvial gradient.

SEQUENCE STRATIGRAPHY

Fluvial Response to Base-level Change

To maintain an equilibrium profile, fluvial systems respond to changes in base level in predictable ways. Fluvial systems respond to changes in base level through aggradation or incision of the fluvial profile as well as through changes to the morphology of the fluvial system (Richards, 1996; Blum and Törnqvist, 2000). A sequence stratigraphic analysis of fluvial systems will distinguish genetically related strata and establish a chronostratigraphic framework for these deposits (Posamentier and Vail, 1988; Shanley and McCabe, 1994). In fluvial systems, base level is defined as an imaginary and dynamic equilibrium surface above which a particle cannot come to rest and below which deposition and burial is possible (Sloss, 1962). Above this surface sediment cannot be deposited, and below this point sediment can be preserved. This surface changes through time. Generally, changes in base level result from changes of gradient and morphology of the fluvial system (Miall, 1989; Schumm, 1993).

A drop in base-level can lead to an increased gradient in fluvial systems resulting in incision (Fisk, 1944; Holland & Pickup 1976; Schumm et al., 1984, 1987; Miall, 1996). Incision occurs through the process of upstream knickpoint migration. The knickpoint is the point along the longitudinal fluvial profile where the gradient increases (Schumm, 1993). Incision may be coupled with other changes in the fluvial system: (1) widening of fluvial channels, (2) a relative decrease in channel sinuosity (3) a change to a coarser, bed-load dominated systems (4) formation of incised valleys which are much wider than the rivers contained within them (Schumm, 1981; Marzo et al., 1988; Van Wagoner et al., 1990). Following a drop in base level, fluvial systems will continue to incise until a new equilibrium profile is reached. This equilibrium profile is not always reached before new equilibrium conditions are established (eg. Grand Canyon, Colorado Plateau).

A base-level rise can decrease the gradient of a fluvial system and result in aggradation (Richards, 1996), which causes reduced stream power, discharge, and the inability of the fluvial system to carry its sediment load (Schumm, 1993). This causes aggradation of the fluvial system. Channels tend to become less bed-load dominant and the sinuosity increases relative to the higher gradient fluvial system (Richards, 1996).

Fluvial systems at equilibrium will not aggrade or incise. Equilibrium occurs if base level remains constant for an extended period of time (Schumm, 1993). During equilibrium conditions, sinuous channels rework laterally through point bar migration and channel meandering (Schumm, 1993). Flood events may cause active meandering channels to build levees and to deposit sediments in surrounding floodplain areas, which can cause a gradient change of the surrounding floodplain (Richards, 1996). During a flooding event, a channel may also breach its levee and begin to follow a new course. This new course will follow the highest gradient of the floodplain (Richards, 1996). Braided systems in equilibrium rework lateral deposits through avulsion, channel switching, and the lateral migration of braid bars (Miall, 1996).

Recognizing a Sequence Boundary in Fluvial Successions

A sequence boundary is initiated by a base-level fall resulting in a loss of accommodation, erosion, incision, and sediment bypass. In fluvial systems, a sequence boundary is recognized by regional truncation of older strata and a basinward shift in facies (Van Wagoner, 1995). The basinward shift in facies may be recognized by a change from lower energy fluvial deposits below the boundary to higher energy fluvial deposits above the boundary (Van Wagoner, 1995). The incision process results in an increase in the gradient of the fluvial system. In this study, the terms high and low-energy fluvial systems are relative. The designation of a fluvial system as high energy denotes that the fluvial system has greater competency, capacity, and flow velocity relative to the low-energy fluvial systems. Higher flow velocities are interpreted from the presence of coarser sediment and larger bedforms.

Dorotea Formation Sequence Stratigraphy

Tops of individual channel-fill sandstones and the time equivalent surfaces in laterally equivalent overbank deposits are parasequence boundaries, which represent base-level rise (Kamola and Van Wagoner, 1995). This rise in base-level allows for the development of accommodation and deposition of thick overbank deposits overlying the channel-fill sandstones. There are at least fourteen vertically stacked parasequences in the lower unit and nineteen in the upper unit. It is likely that more parasequences are present but are not identified, because parasequence boundaries are difficult to recognize in poorly weathered, thick, overbank deposits. There is little variability in the vertical stacking of these parasequences in the study area. The fluvial characteristics (i.e. average channel-fill sandstone thickness, cross-bed thickness, average grain size) do not change between parasequences indicating that there is no trend in the parasequence stacking (e.g. backstepping or progradation of facies) from the base to the top of the unit. This lack of a vertical trend suggests that the parasequences are aggradationally stacked. A progradational or retrogradational stacking pattern would result in a vertical change in stacking pattern (i.e. progressive increase or decrease in energy of fluvial facies, or thickness in overbank deposits in overlying parasequences).

In the lower unit, parasequences are easily recognized, with each parasequence representing the formation and subsequent filling of the accommodation by single-story channel-fill sandstones, and laterally equivalent floodplain fines. Easily recognizable parasequences indicate that accommodation is formed in episodic/intermittent pulses, rather than in a slow, continuous process. A slow and continuous formation of accommodation would result in an aggradationally stacked channel system with slight lateral reworking (Van Wagoner, 1995; Richards, 1996). The lateral continuity of the channel-fill sandstones is limited, resulting in isolated channel-fill sandstones encased in overbank deposits (Richards, 1996). This is due to accommodation for parasequences developing quickly, and is characterized by a high accommodation to sediment supply ratio (Richards, 1996).

The stratal patterns observed within the Tres Pasos and Dorotea formations record accommodation throughout the final stage of fill of the basin, and record the complex interaction between eustatic fluctuations and tectonic subsidence. Distinguishing between these processes and which process controlled stratal development is difficult. Eustatic falls formed sequence boundaries, but tectonic uplift increased fluvial gradient and formed regional erosion surfaces in the proximal part of the basin dominated by fluvial fill. If preserved, these too would become sequence boundaries in the rock record. Eustatic changes would have formed depositional sequence, but the net accommodation due to tectonic subsidence allowed for the preservation of depositional sequences. Accommodation needed for development of parasequences in the lower unit of the Dorotea Formation could reflect episodic thrust movement in the thrust belt. This mechanism was proposed for parasequence development in the Upper Cretaceous Blackhawk Formation of the Sevier foreland basin in North America (Kamola and Huntoon, 1995).

Sequence boundaries are not identified within the lower or upper unit of the Dorotea Formation. Within each unit, there are no abrupt changes in fluvial morphology, substantial increases in grain size, or increases in cross bed thickness that could be interpreted to reflect a base-level fall or sequence boundary (e.g. Shanley and McCabe, 1995). Those features are only found at the contact between the two units. The sequence boundary observed at the formation contact between the Dorotea and Tres Pasos formations in the study area is a major unconformity. The substantial basinward shift in facies at the formation contact and the erosion of shallow marine section from the top of the Tres Pasos Formation may have been caused by global sea-level fall or by the forward propagation of thrusts and possible blind thrusts in the Patagonian fold-and-thrust belt.

PETROGRAPHIC ANALYSIS

Petrographic analysis allows for the determination of composition and grain-type abundance within each sample. This analysis is used to determine lithologic trends within sample locations and within the Tres Pasos and Dorotea formations in the study area of the Magallanes Basin.

Modal composition of sandstone samples was determined using the Gazzi-Dickinson Point Counting Method (Dickinson, 1970). A total of three hundred points were counted on each thin section, and then normalized to quartz, feldspar, lithic (QFL), as well as polycrystalline quartz, feldspar, total lithic (QmFLt) parameters (Table 1). These parameters were plotted on ternary diagrams using provenance fields determined by Dickinson (1985)(Fig. 5). The Gazzi-Dickinson Method was chosen because of its emphasis on tectonic setting and its effect on the source area of detrital sandstones. It also eliminates bias related to grain size. The populations represented in each diagram include detrital framework grains. Samples from the outcrops were impregnated with blue epoxy and etched for feldspar on half of the thin section. Analysis was completed on four thin sections from each measured section (Arroyo Calafate-RIO, Aerosilla-ARO, Alta Vista, AV). Four thin section samples were used from the Arroyo Calafate measured section, one sample from facies 2 (Dorotea – lower unit), and three from facies 4 (Dorotea – upper unit). Using point count data, samples were then classified, and descriptions were developed recording textural and mineralogical maturity. The Folk Method (Folk, 1968) of rock classification was chosen and the Folk QFL plot was used to classify each sample for this study.

Petrography

Quartz, feldspar, and lithic grains are the three categories used in the analysis for this study. The quartzose component includes both monocrystalline quartz (Qm) and polycrystalline or microcrystalline quartz (Qp). The Qm contains minor inclusions, has quartz overgrowth, and is often fractured. The Qp is mostly chert grains.

The feldspathic component of the point-count analysis includes plagioclase feldspar. Although, alkali feldspar is not identified in any of the samples obtained, plagioclase feldspar is identified on the basis of its twinning extinction. In particular, plagioclase feldspar is seen with polysynthetic twinning, which is either albite or pericline. In some samples, feldspar grains are seen with a high degree of alteration making specific identification difficult.

The lithic components (L) for this study were divided into two categories and based on texture and mineralogy – (1) volcanic/metavolcanic lithic fragments (Lv) and (2) sedimentary/metasedimentary lithic fragments (Ls). The volcanic/metavolcanic lithic component includes abundant siliceous volcanic fragments, variable amounts of andesitic volcanic fragments, tuffaceous clasts, and a minor contribution of quartz-rich clasts. Sedimentary type lithic grains include sandstone fragments, mudstone fragments, and siltstone fragments.

Rock type was determined for each sample by plotting the individual QFL data on a QFL Folk diagram (modified Folk, 1968). The data from this analysis have the Tres Pasos and Dorotea formations plotted as a litharenite rock type. Observations of accessory minerals show vertical changes across the sequence boundaries. The Tres Pasos Formation shows evidence of zircon, chlorite, tourmaline, mica, and spinel. The overlying Dorotea Formation has mica, chlorite, and zircon, but in sparse amounts. A trend was observed from the base to the top of the Dorotea Formation. Accessory minerals decreased up section, and a majority of them were absent at the top of the section.

Discussion of possible source terranes

Fildani & Hessler (2005) and Fildani et al. (2003) reviewed potential source areas for the Zapata, Punta Barrosa, Cerro Toro and Tres Pasos formations that are exposed along the Andean orogenic belt. A predominant south to southeast paleotransport has been proposed for the Dorotea and Tres Pasos formations in the Chilean section of the Magallanes Basin (e.g. Katz, 1963; Scott, 1966; Smith, 1977; Winn & Dott, 1979; Dott et al., 1982; Wilson, 1991; Fildani & Hessler, 2005; Shultz et al., 2005; Crane & Lowe, 2008; Hubbard et al., 2008; Armitage et al., 2009; Romans et al., 2009). Paleocurrent analysis from this study supports this conclusion. The south/southeast paleocurrent finding allows for the elimination of possible source terranes from the south, such as the Antarctic Peninsula Batholith (Thomson & Pankhurst, 1983; Millar et al., 2002) and the Beagle and Darwin granites (Nelson et al., 1980). Even without the paleocurrent analyses, an easterly source of sediment can be ruled out because the Argentine craton during this time was a broad depositional platform of fine-grained sediment (Biddle et al., 1986). The western and northwestern terranes of the Andean Belt have been interpreted to be significant source areas for the Magallanes basin during the Cretaceous (Wilson, 1991, Fildani et al., 2003, Fildani & Hessler, 2005; Calderon et al., 2007). These include the pre-Upper Jurassic metamorphic complexes, the Upper Jurassic rift-related silicic volcanic rocks, the Upper Jurassic mafic rocks, and the Jurassic to Tertiary continental arc.

Using QFL diagrams of Dickinson and Suczek (1979), sandstones of the Tres Pasos and Dorotea formations plot along the Q-L line, in the field of recycled orogen. Samples plot in the transitional to lithic recycled fields in the QmFLt diagram (Fig. 5). Sandstones are comprised of quartz fragments, with undular extinction, metaquartzite fragments, and siliceous volcanic rocks with some andesitic volcanic fragments. This suggests possible derivation from the magmatic arc to the west, the Tobífera duplex growth, and possibly the Tenerife thrusting, which incorporates basin fill into the fold-and-thrust belt.

No major trends in the compositional analysis were detected within either the Dorotea or Tres Pasos formations. This indicates that there is not a substantial change in source area during the time of deposition, which aligns with the previous studies of provenance for these two formations (Smith, 1977; Macellari et al., 1989; Romans et al., 2010).

The observations of accessory minerals in the Tres Pasos and Dorotea formations show a greater abundance in the Tres Pasos Formation. The Lower Dorotea Formation contains the same, accessory minerals, but they are in lower concentrations. This is interpreted to the reworking of sediment of the Tres Pasos Formation (i.e. Tres Pasos Fm was a source rock for the Dorotea Fm). The loss in accessory minerals at the top of the Dorotea Formation section could have been caused by the fluvial system no longer reworking sediment derived from the underlying Tres Pasos Formation.

The results of this study more closely resemble data compiled by Macellari et al. (1989) and Smith (1977), but show slightly more quartz and lacks feldspar when compared to analyses by Romans et al., (2010). Romans et al., (2010) analyzed samples from the Chilean section. The data from this study plot samples of the Tres Pasos and Dorotea formations as litharenites, whereas Romans et al., (2010) plotted the Chilean samples as feldspathic litharenite. This may be a reflection of a fundamental segmentation in the Andes at approximately 49° S, separating the Aisén segment to the north from the Magallanes segment to the south (Aguirre, 1985). This segmentation is located at the present intersection of the Chile Rise with the continent, and also coincides with the northernmost extension of the Lower Cretaceous Rocas Verdes basin (Aguirre, 1985).

CONCLUSIONS AND IMPLICATIONS FOR BASIN DEVELOPMENT

This study presents an integrated analysis to determine depositional environments of the Late Cretaceous to Paleogene strata of the Tres Pasos (upper 10%) and Dorotea formations, place these strata in a sequence stratigraphic framework, study the transition from the Tres Pasos and Dorotea formations in the field and using thin-section petrography, and perform a paleocurrent analysis to better understand the basin-fill history. This study shows that an integrated stratal architecture based on a detailed depositional analysis provides important information about basin development: (1) It interprets the Dorotea and Tres Pasos Formation contact is a sequence boundary in the Lago Argentino section, (2) there is no significant change in source area between these two formations, and (3) the stratal patterns record a basinward migration of facies thought to be caused by the forward propagation of thrusts in the Patagonian fold-and-thrust belt.

Strata of the Dorotea Formation, previously interpreted as shallow marine, are reinterpreted in this study to be channel-fill sandstone and overbank deposits. The contact between the Tres Pasos Formation and Dorotea Formation is an erosional contact, which differs from the Chilean section (~25 km to the SW), where it has been reported as a continuous transition from slope to shelf subenvironments (Macellari et al., 1989; Fildani et al., 2008; Covault et al., 2009; Hubbard et al., 2010; Fosdick et al., 2011; Romans et al., 2011). This formation contact in the study area is a major unconformity. Missing section may have been eroded by a due to a substantial basinward migration of facies, suggesting a major regional unconformity and sequence boundary formed by a global sea-level fall or blind thrust. The petrographic analysis of this study shows that there are no notable changes in source area during the transition of deposition from the Tres Pasos Formation to the Dorotea Formation. It also shows that there are no major changes in source throughout the deposition of the Dorotea Formation.

The Dorotea Formation is divided into two informal stratigraphic units, one dominated by lower energy, low-sinuous meandering channel-fill sandstones, and one dominated by a higher energy, braided channel-fill sandstones with conglomerates. The strata within the lower part of the lower Dorotea Formation contain channel-fill sandstones that average 5.5 m, and show some marine influence. Channel-fills within the higher energy upper unit are thicker (averaging 7.6 m), coarser grained and reflect an increase in fluvial gradient.

Stratal patterns within the Tres Pasos and Dorotea formations record changes in accommodation throughout the final stage of fill of the Magallanes foreland basin. The stratal patterns seen within the Tres Pasos and Dorotea formations are proposed to record the interaction between eustatic fluctuations and tectonic subsidence. Eustatic falls are proposed to control base level drop, which formed the sequence boundaries. Depositional sequences are preserved due to both tectonics and subsequent subsidence, and eustatic change. Without net accommodation due to tectonic subsidence, sediment is repeatedly reworked in the same space, and only the youngest event will have a depositional record, even though multiple base-level oscillations may have occurred. The forward propagation of thrusts in the Patagonian fold-and-thrust belt can result in a basinward shift of facies through time, and form significant unconformities, such as the unconformity between the Tres Pasos Formation and the overlying Dorotea Formation.

FIGURES AND TABLES

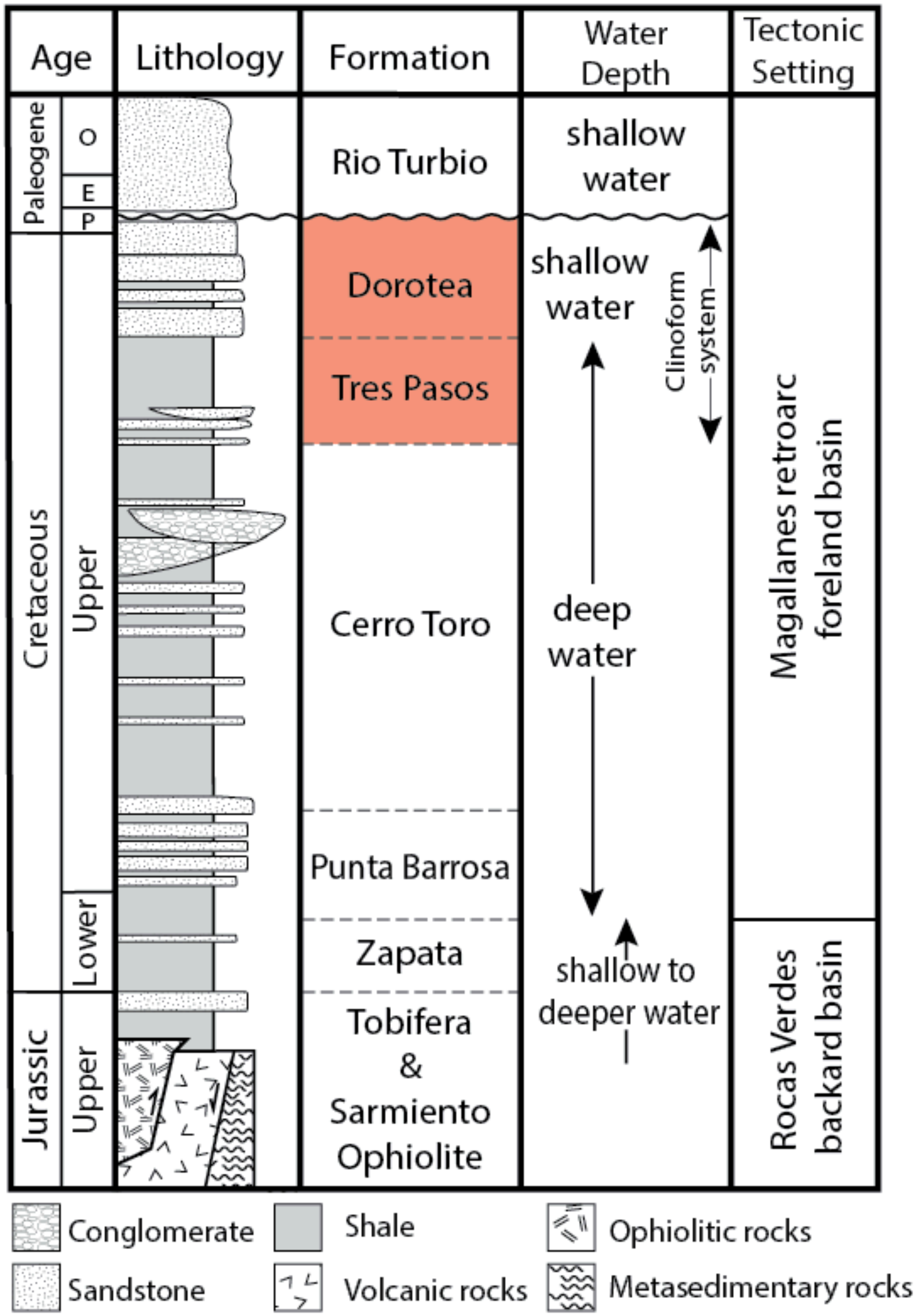

Figure 1. Generalized stratigraphic section from the Ultima Esperanza district of Chile at Cerro Cazador, 75 km south of the study location. The highlighted formations are the focus of this study. Modified from Romans et al. (2010); originally adapted from Fildani and Hessler (2005) and Wilson (1991).

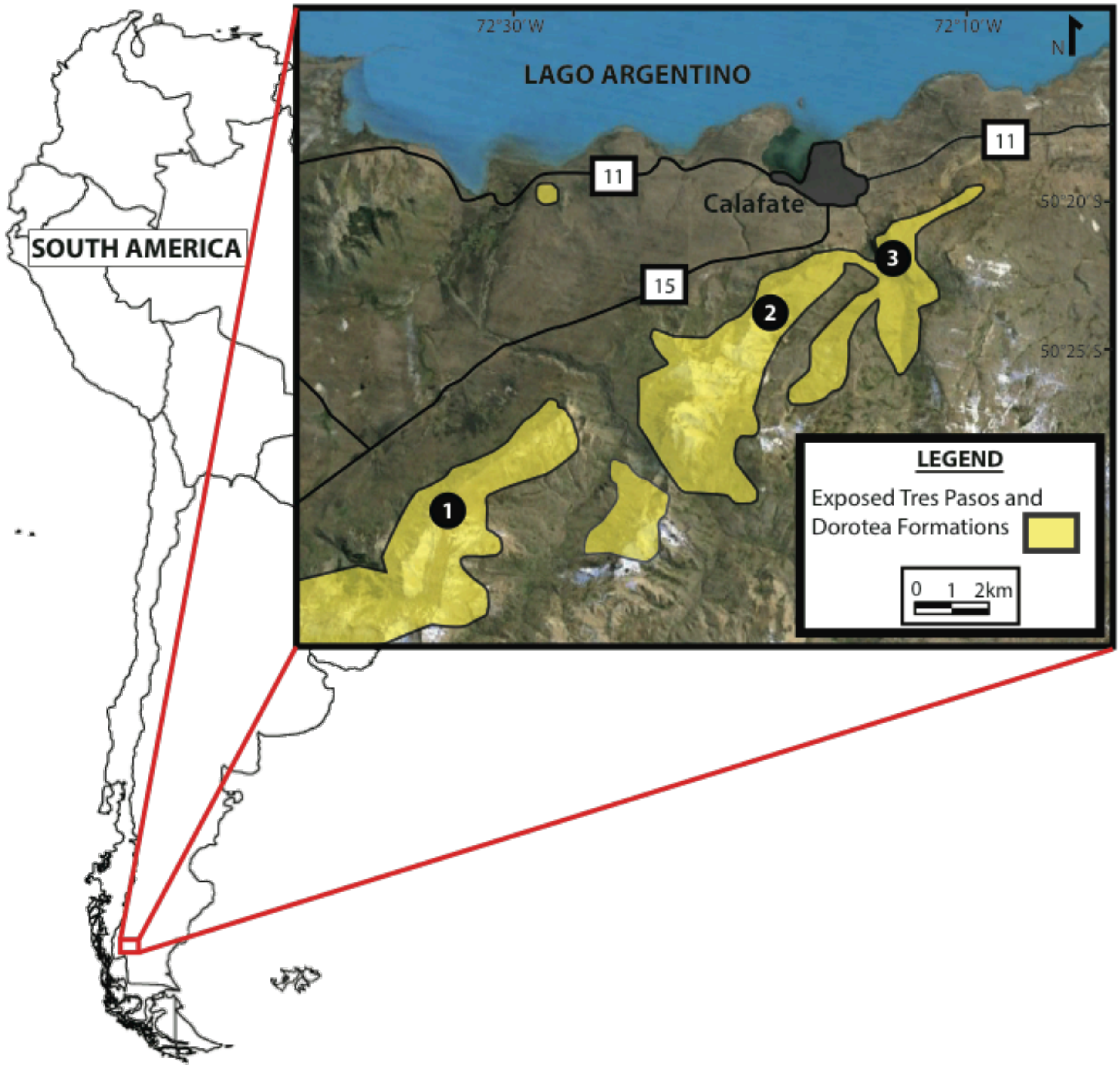

Figure 2. Location map of the study area showing the southern side of Lago Argentino near El Calafate, Argentina. The numbers refer to the measured sections: 1)Alta Vista; 2) Aerosilla; 3) Arroyo Calafate (Modified from Google Earth and Cuitiño et al., 2012).

Measured Sections

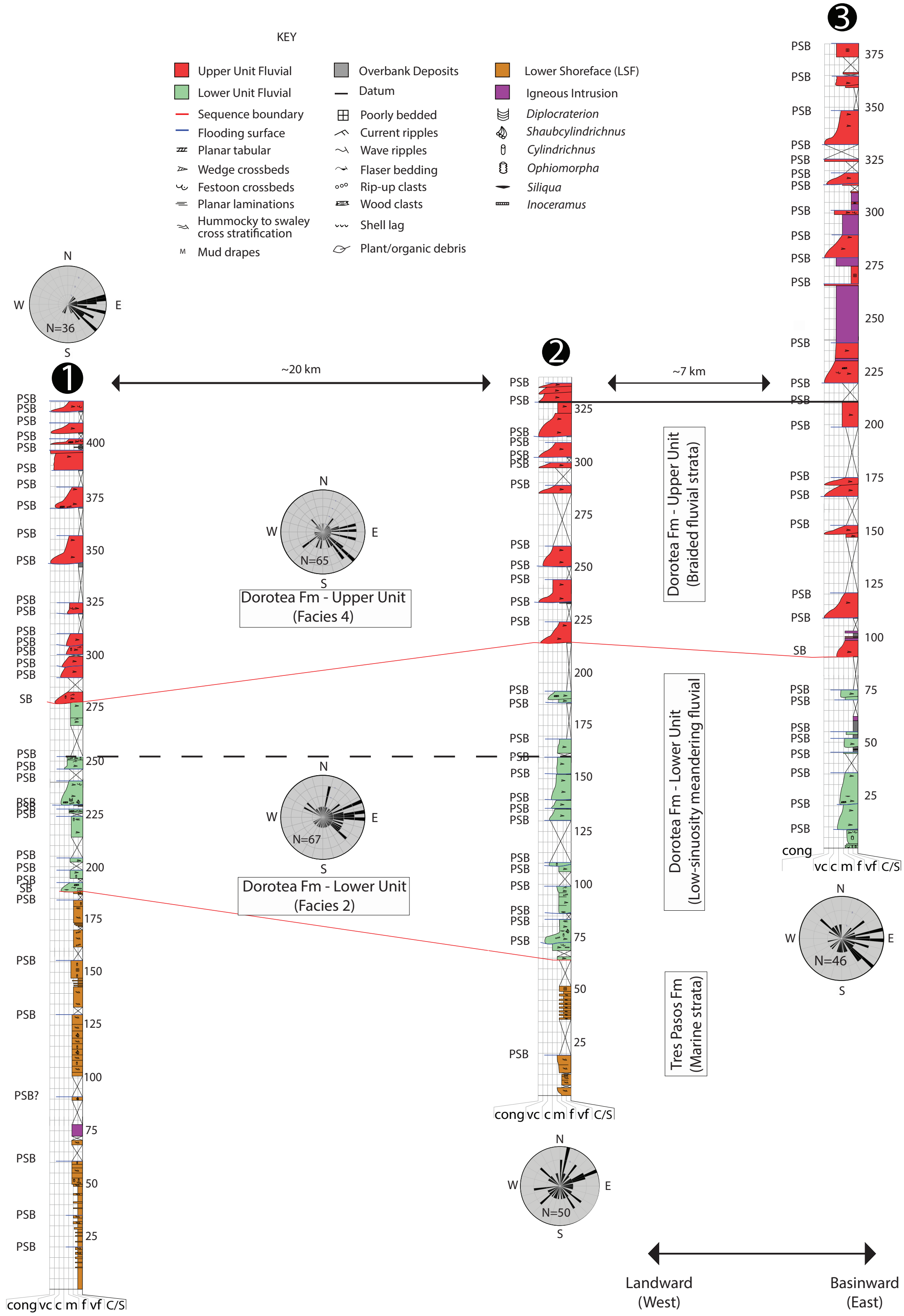

Figure 3. Correlated stratigraphic sections of the upper Tres Pasos and Dorotea formations at the study location. Locations of measured sections 1, 2, and 3 are found in figure 1. Paleocurrent data show a predominant flow direction to the east and southeast.

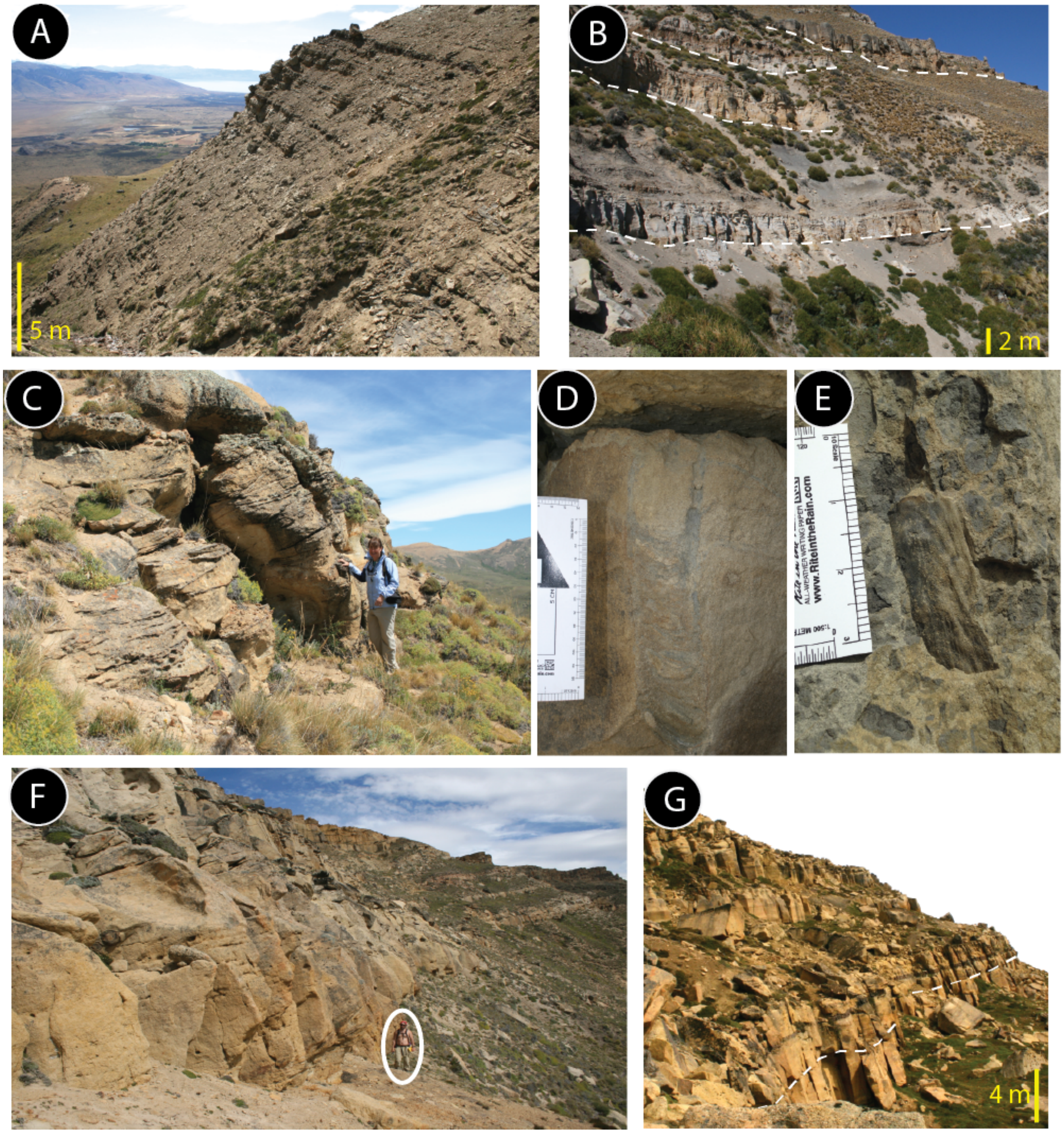

Figure 4. Compilation of photographs showing observed facies in the Tres Pasos and Dorotea formations. (A) Upward-coarsening succession of interbedded resistant sandstone (hummocky to swaly cross-stratification) and less resistant thinly bedded siltstones, Tres Pasos Formation. (B) Lower unit of the Dorotea Formation showing isolated channel-fill deposits encased in fine-grained deposits. Dashed-white lines outline the scour base of several channel-fills. (C) Trough-cross stratification, lower unit – Dorotea Formation. (D) *Diplocraterion* in channel-fill sandstone, lower unit – Dorotea Formation. (E) Abraded shell along bedding plane, *Siliqua* in lower unit – Dorotea Formation. (F) 9 m channel-fill sandstone of the upper unit – Dorotea Formation. (G)

Amalgamated, laterally continuous channels of the upper unit – Dorotea Formation. Dashed-white line outlines the scour base of an amalgamated channel-fill sandstone.

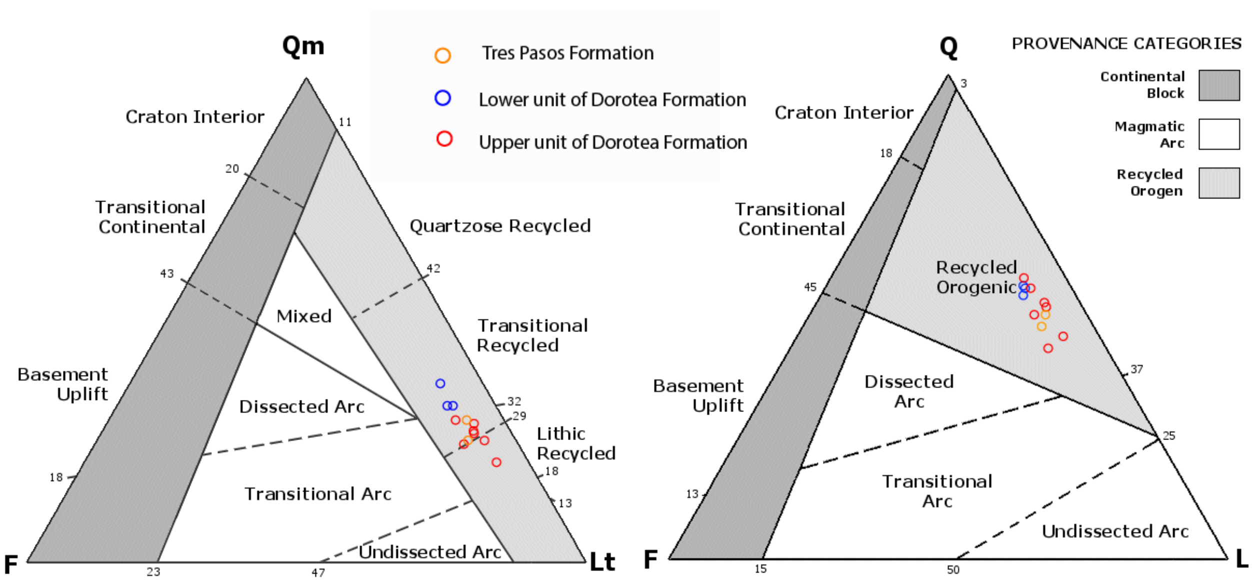

Figure 5. Quartz-feldspar-lithics (QFL) and monocrystalline quartz-feldspar-total lithics (QmFLt) ternary plots for sandstone from the Tres Pasos and Dorotea formations from this study; Tectonic fields from Dickinson (1985).

Table 1. Proportions of detrital grains for the Tres Pasos and Dorotea formations in Santa Cruz Province, southern Argentina. Point counts include only framework grains.

Sample	Formation	Location	Facies	Q	F	L	Qm	F	Lt
Rio E	Dorotea	Arroyo Calafate	2	55	9	36	32	9	59
Rio W	Dorotea	Arroyo Calafate	4	54	6	41	25	6	70
Rio An	Dorotea	Arroyo Calafate	4	44	10	46	24	10	66
Rio AU	Dorotea	Arroyo Calafate	4	52	6	41	28	6	65
Tres Pasos ARO	Tres Pasos	Aerosilla	1	51	7	42	29	7	64
P2 ARO	Dorotea	Aerosilla	2	57	8	35	32	8	60
AL ARO	Dorotea	Aerosilla	4	46	6	47	20	6	73
AV ARO	Dorotea	Aerosilla	4	58	7	34	26	7	66
AV T	Tres Pasos	Alta Vista	1	49	9	43	25	9	67
AV AG	Dorotea	Alta Vista	2	57	8	36	37	8	56
AV AV	Dorotea	Alta Vista	4	51	9	40	29	9	62
AV BF	Dorotea	Alta Vista	4	57	7	37	27	7	67

Q, quartz; F, feldspar; L, lithic fragments; Qm, monocrystalline quartz; Lt, lithic fragments including polycrystalline quartz; Qp, polycrystalline quartz; Lv, volcanic lithic fragments; Ls, sedimentary and metasedimentary lithic fragments. See figure 1 for sample locations. Each sample consists of 300 counts. See figure 6 for QFL and QmFLt ternary plots.

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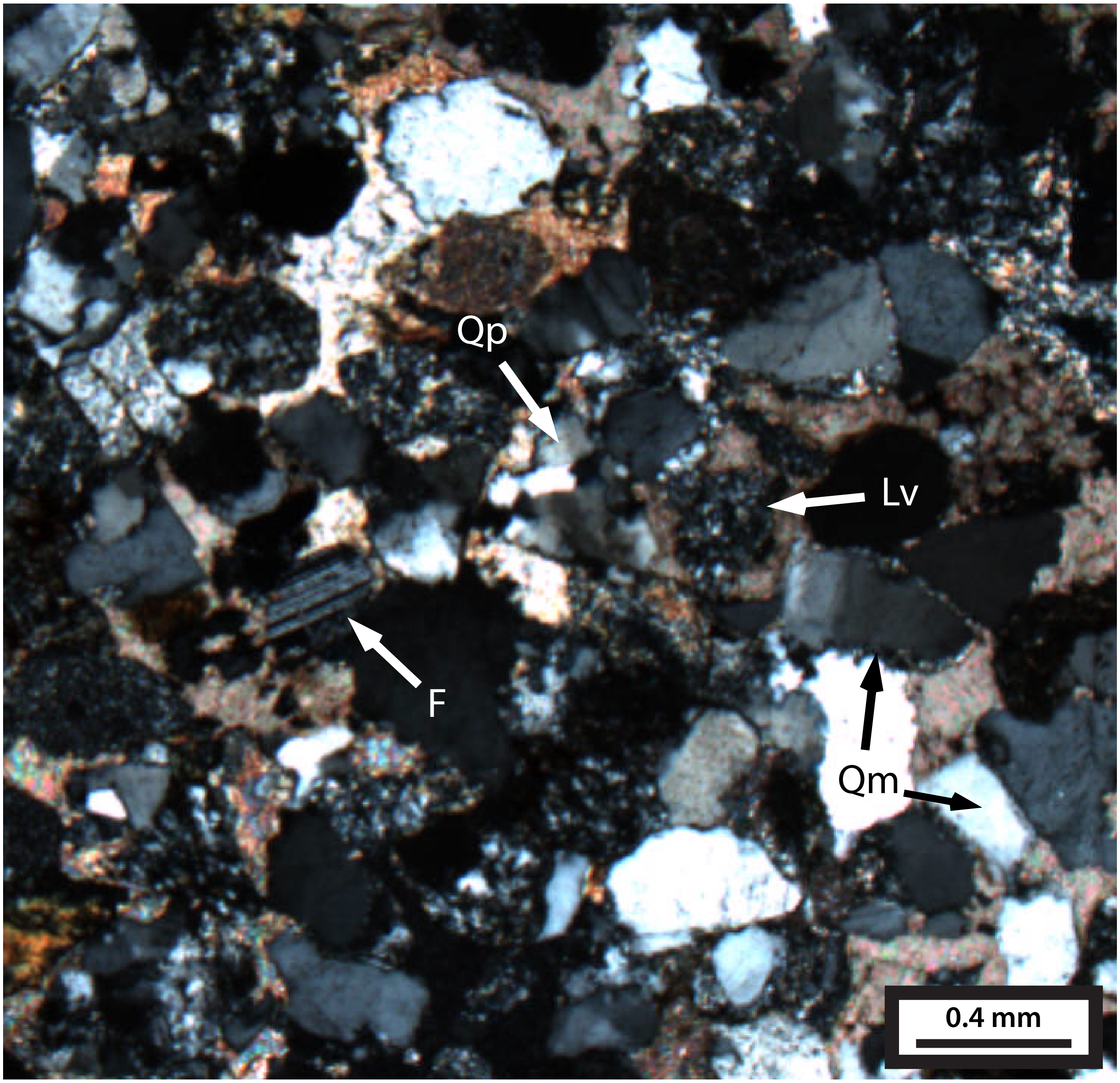
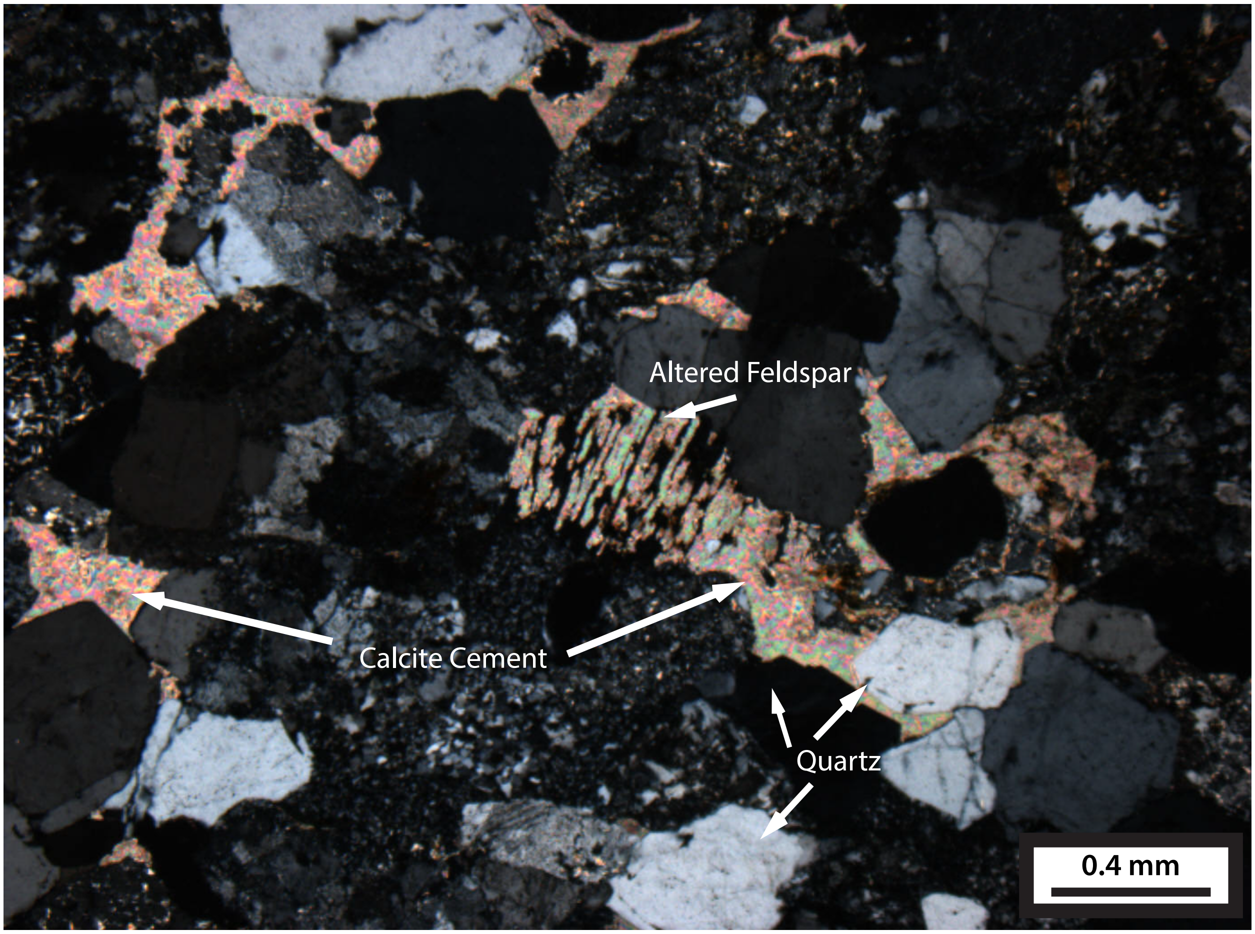
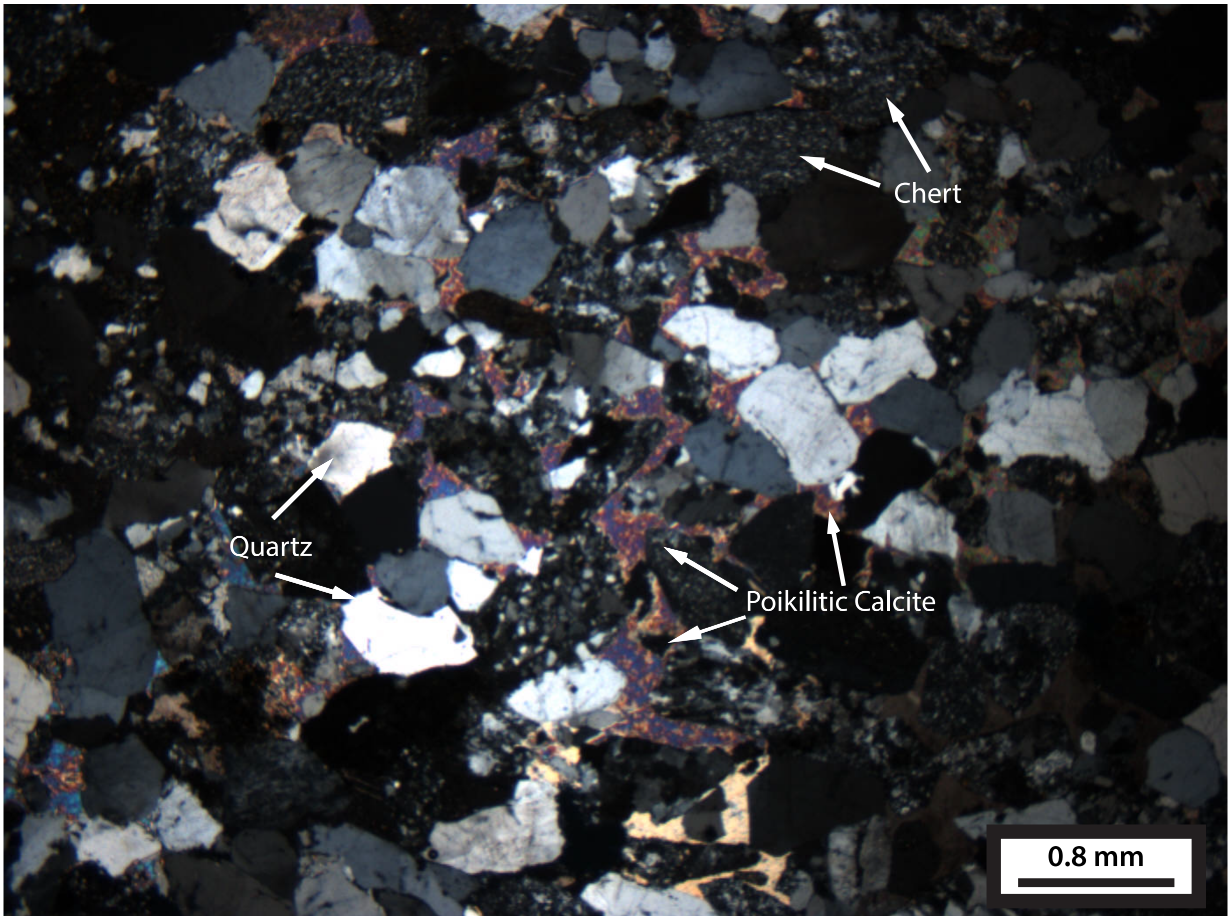
APPENDIX



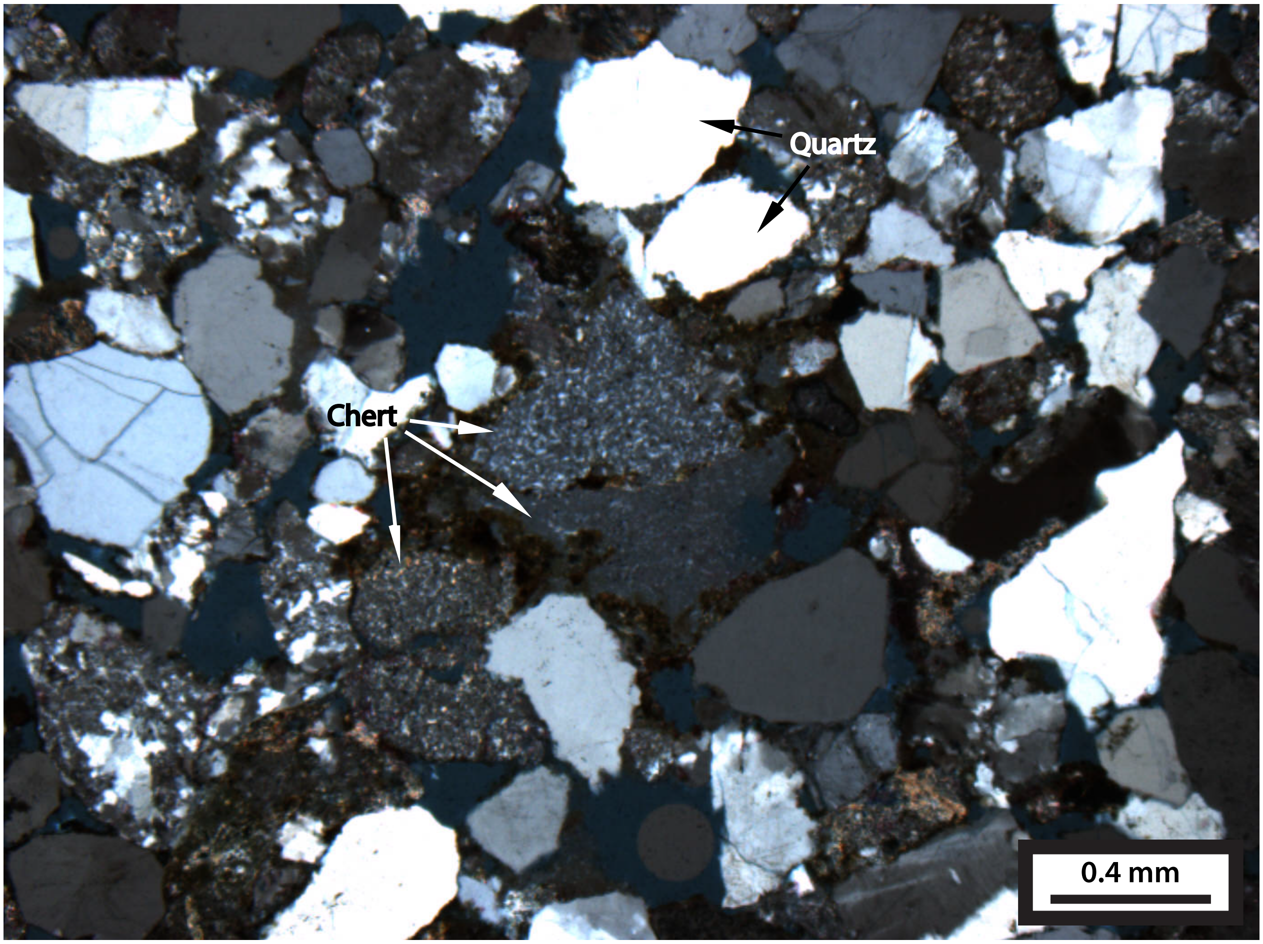
Photomicrograph of Rio AN showing quartz, feldspar and lithic grains in cross-polarized light. The quartz consists mainly of monocrystalline quartz (Qm) grains with undulose and nonundulose extinction and polycrystalline quartz (Qp) grains. Plagioclase feldspar (F) grains are seen with polysynthetic twinning, which is either albite or pericline. The lithic component is seen here as volcanic lithic (Lv) grains.



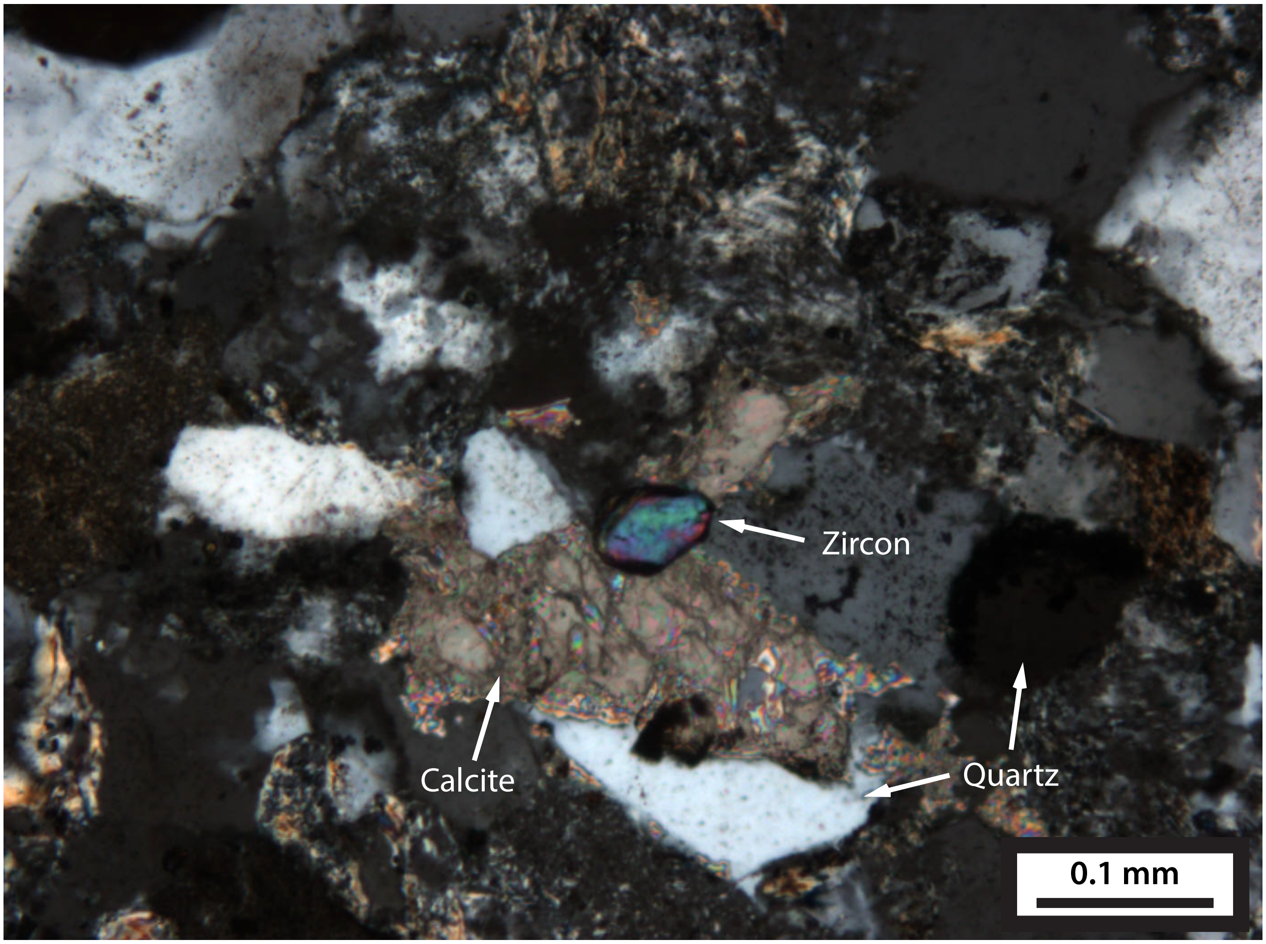
Photomicrograph of Alta Vista BF showing altered feldspar in cross-polarized light. The potassium feldspar has been altered and been replaced by calcite cement showing high birefringence.



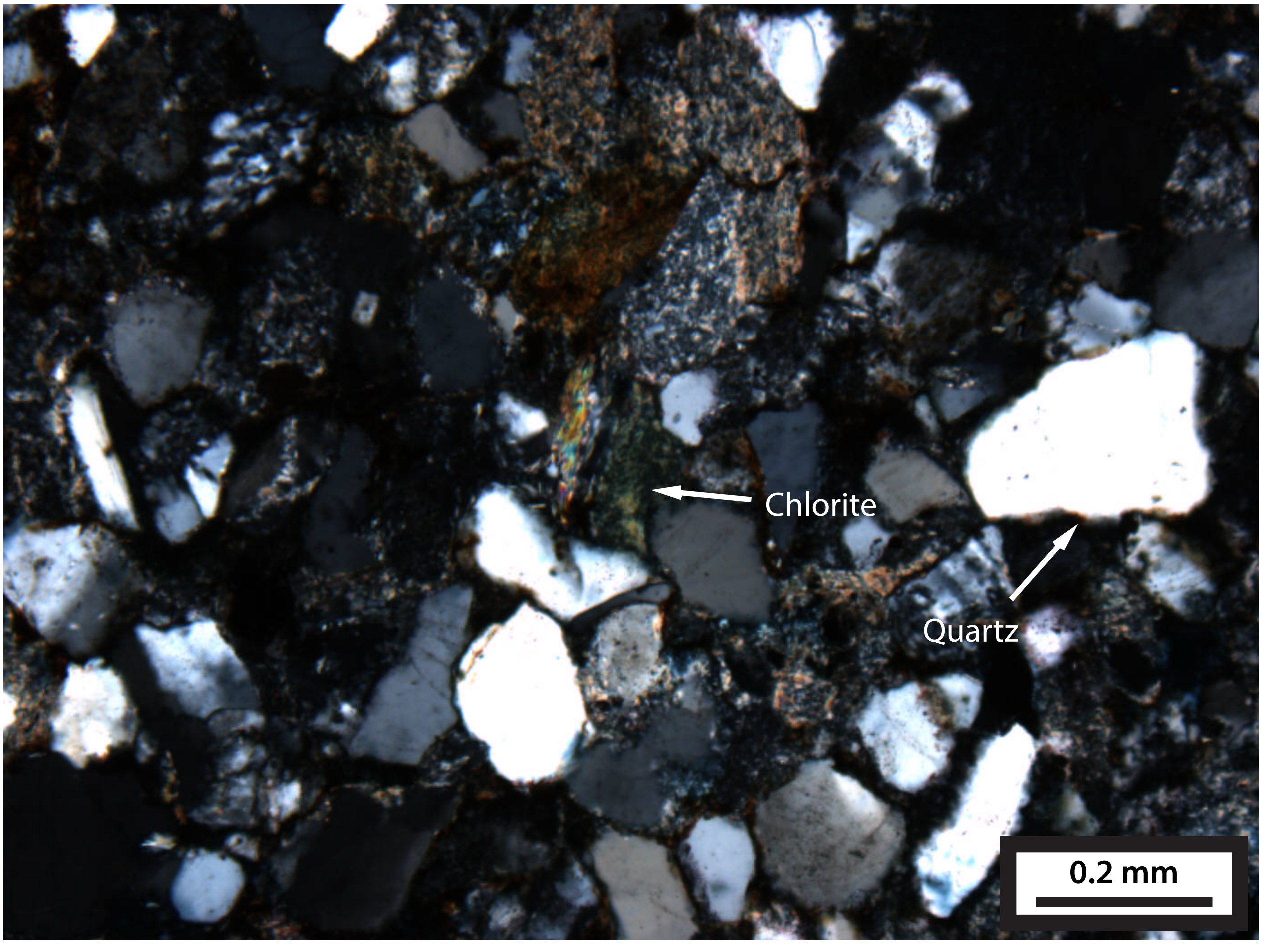
Photomicrograph Alta Vista BF showing poikilitic calcite cement in cross-polarized light.



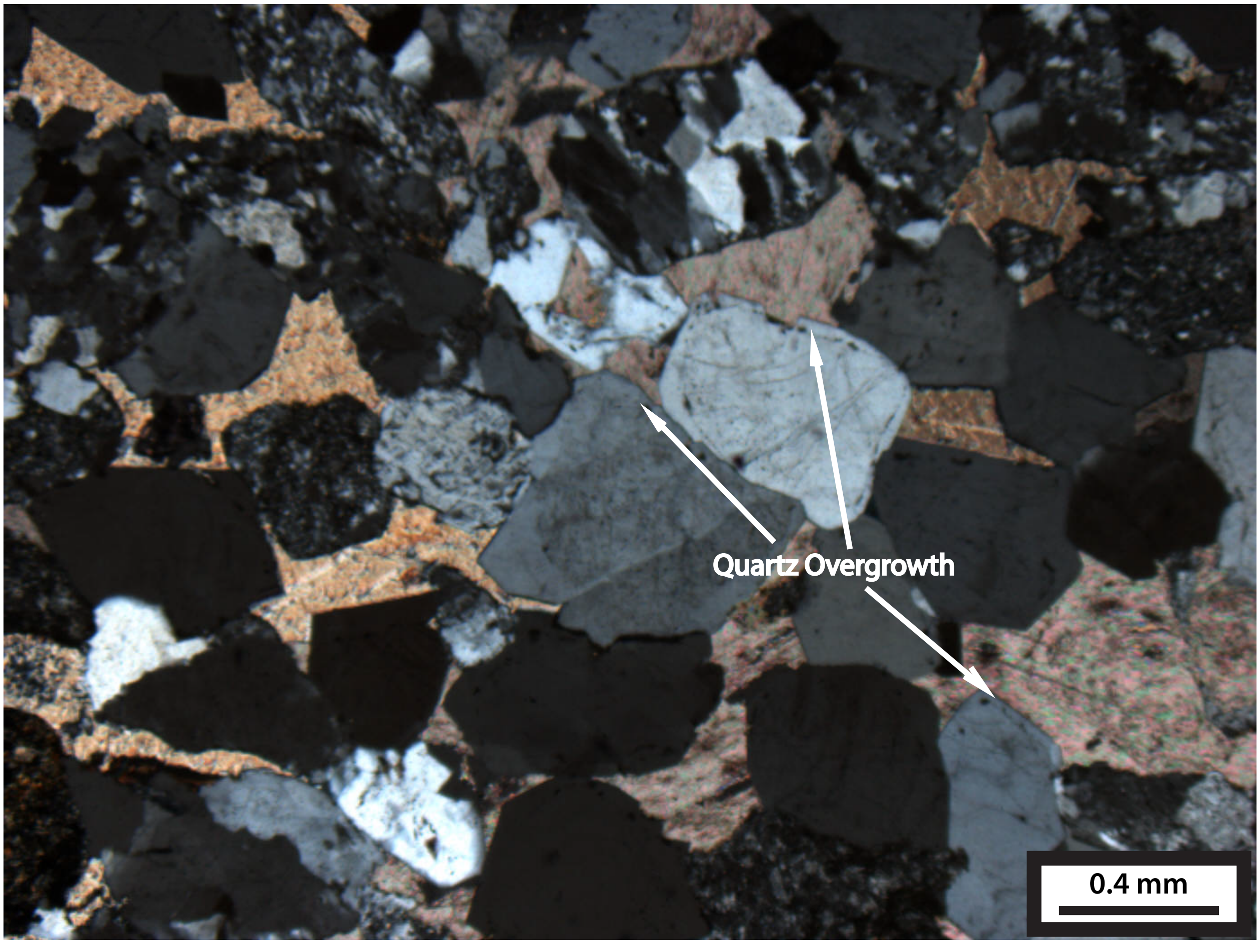
Photomicrograph of AV AG showing an abundance of chert in cross-polarized light.



Photomicrograph of AV T showing a zircon with high birefringence in cross-polarized light.



Photomicrograph of P2 ARO showing a fragment of chlorite in cross-polarized light.



Photomicrograph of AV ARO showing quartz overgrowth on quartz sands surrounded by calcite cement in cross-polarized light.

KEY

Upper Unit Fluvial

Lower Unit Fluvial

Overbank Deposits

Lower Shoreface (LSF)

Igneous Intrusion

Sequence boundary

Flooding surface

Planar tabular crossbeds

Wedge crossbeds

Festoon crossbeds

Planar laminations

Hummocky to swaley cross stratification

M Mud drapes

Poorly bedded

Current ripples

Wave ripples

Flaser bedding

Rip-up clasts

Wood clasts

Shell lag

Plant/organic debris

Diplocraterion

Shaubcylindrichnus

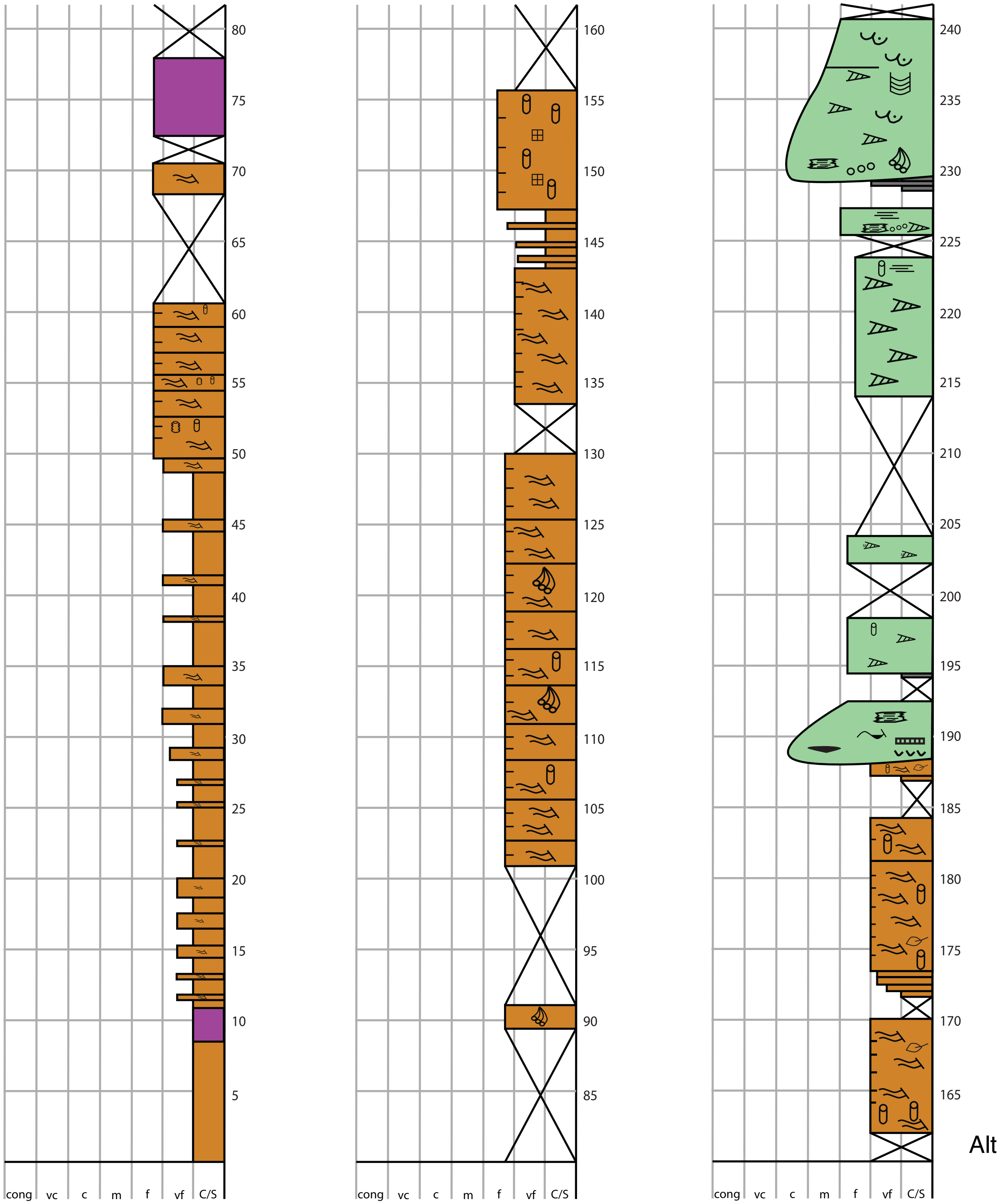
Cylindrichnus

Ophiomorpha

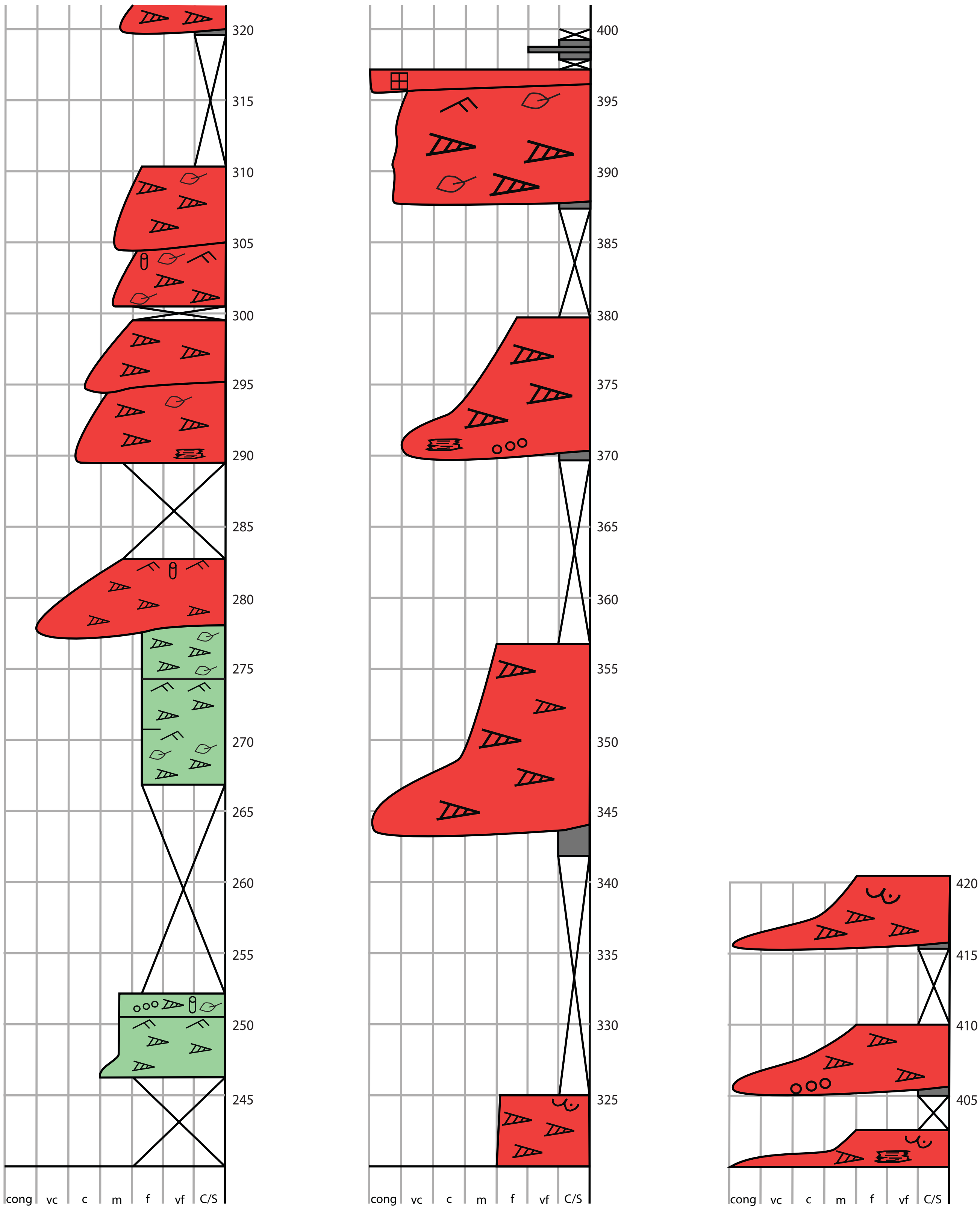
Siliqua

Inoceramus

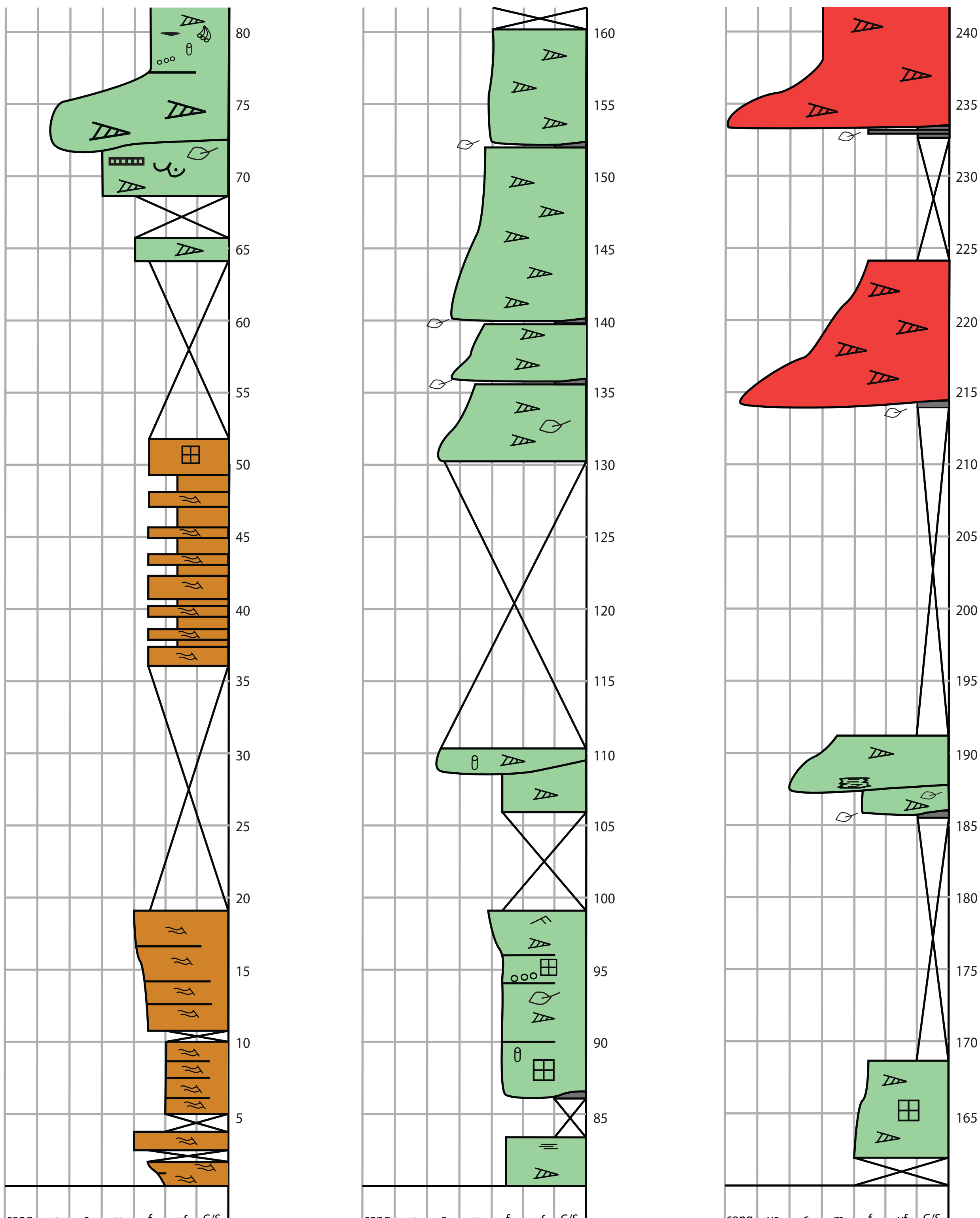
AltaVista Measured Section



Alta Vista Measured Section



Aerosilla Measured Section



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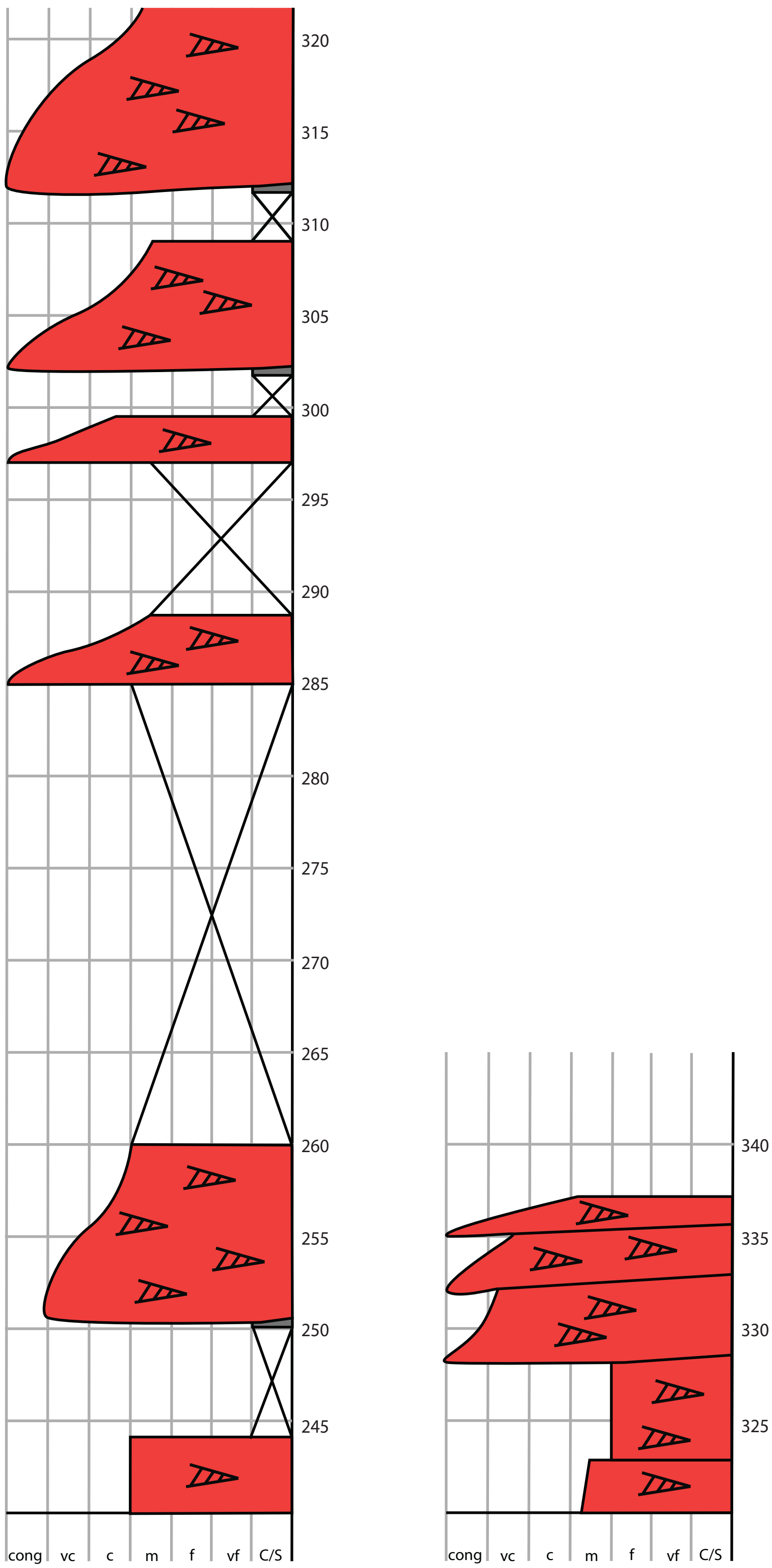
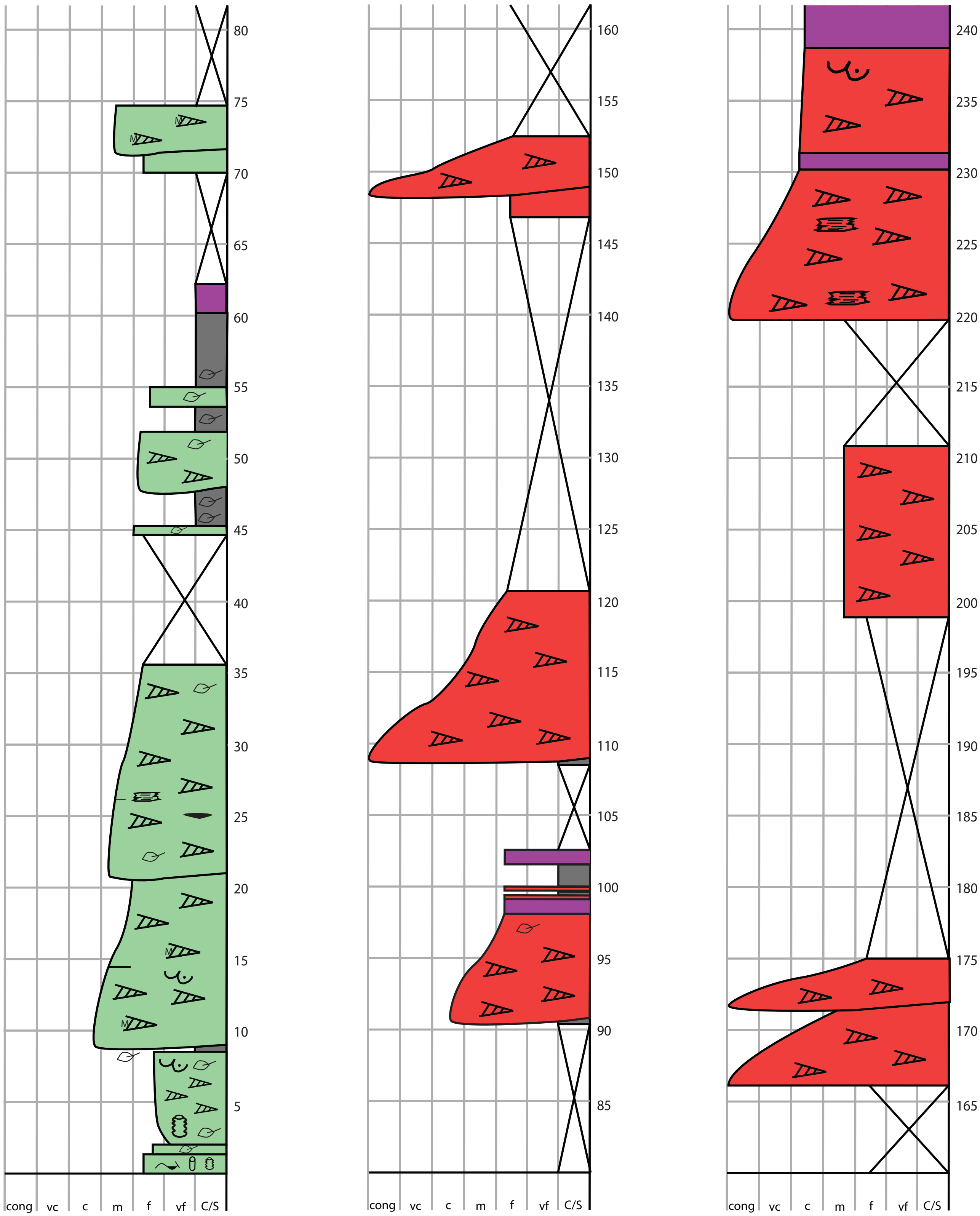


Arroyo Calafate Measured Section



Arroyo Calafate Measured Section